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METHOD AND APPARATUS FOR NON-DESTRUCTIVELY

DETERMINING FEATURES IN A PLANAR SPECIMEN

STATEMENT OF GOVERNMENT INTEREST

[0001]   The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002]   None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003]   The present invention is directed to non-destructive testing and more particularly to a method for detecting microscopic structures within a specimen.

(2) Description of the Prior Art

[0004]   Optical microscopes are commonly used to discern small features embedded in specimens. Electron microscopes are also used to discern small features which can be imaged. Electron microscopes exhibit a significantly lower diffraction limit than optical microscopes because the wavelengths of electron beams are much smaller than wavelengths of light. However, electron microscopes are much more expensive than optical microscopes and further require that the specimens be tested in a vacuum.

[0005] Photothermal frequency scan imaging is used for materials analysis in semiconductor manufacture. In photothermal frequency scan imaging a sample is subjected to a pulsed laser. This can be used to detect surface conditions of the sample, but it has only been found to be effective for a limited depth in the sample. These methods have had problems with internal reflections in smaller samples. These methods have also been used as an indication of homogeneity within a sample and also for determining thermal properties within the sample. These methods have not been used to image individual discontinuities within a sample.

SUMMARY OF THE INVENTION

[0006] Accordingly, it is an object of the present invention to provide a method and apparatus for detecting features embedded in specimens;

[0007] Another object is to provide method and apparatus that can detect features without subjecting the specimen to vacuum; and

[0008] Yet another object is to provide a method and apparatus that can detect features without expensive equipment.

[0009] In view of these objects, there is provided a method and apparatus for non-destructively determining features in a planar specimen that includes providing a heat impulse to the

specimen, detecting temperatures in the specimen at a plurality of locations, and imaging the specimen from the detected temperatures. A laser can be used to provide a single or a plurality of heat impulses to the specimen. Temperatures in the specimen can be detected utilizing a contact sensor array or a remote infrared detector. These sensors are joined to a data processing device to image the specimen utilizing the detected temperatures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]   Reference is made to the accompanying drawings in which are shown an illustrative embodiment of the invention, wherein corresponding reference characters indicate corresponding parts, and wherein:

[0011]   FIG. 1 is a diagrammatic view of one method illustrative of an embodiment of the invention;

[0012]   FIG. 2 is a block diagram further illustrative of the embodiment of FIG. 1; and

[0013]   FIG. 3 is a block diagram illustrative of an alternative embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0014]   The transient conduction of heat is typically treated as a diffusion process; however, if the heat source is periodic in nature, heat can propagate in a wavelike manner. This can be

shown by examining the one-dimensional transient heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

wherein α is the thermal diffusivity; T is the temperature; t is time; and x is the spatial dimension. If the temperature has a harmonic time dependence (e.g., as a result of a pulsed laser) then:

$$T(x,t) = \tau(x)e^{-i(\omega t - kx)} \qquad (2)$$

wherein $\omega = 2\pi f$ (and f is the pulse frequency), then equation (1) can be written in the form:

$$i\omega\tau = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (3)$$

having the solution:

$$T(x,t) = T_0 e^{i(\omega t - kx)} \qquad (4)$$

where:

$$k = \omega/c = \sqrt{-i\omega/\alpha} \qquad (5)$$

[0015]   The above solution for T(x,t) is analogous to the solution to the acoustic wave equation. However, the propagation speed of these temperature waves is much slower than

that of acoustic waves. (Temperature waves propagate at 10 m/s and acoustic waves propagate at 5,000 m/s for most solids.) Attenuation is also much higher for temperature waves than for acoustic waves.

[0016]   Use of temperature waves gives advantages and disadvantages when compared with other types of radiation. Temperature waves are distinct from infrared (IR) waves, which propagate at the speed of light. Many materials block infrared waves, but even if the infrared waves are not blocked, their wavelengths are much longer than those of the temperature waves and 10 nanometer resolution is impossible. Infrared sensors thus receive the same signal in each closely spaced sensor.

[0017]   The formula for the wavenumber equation (5) implies that the propagation speed $c = \sqrt{i\omega\alpha}$ varies with the radial frequency, ω. This means that the propagation speed associated with the higher-frequency energy travels at a faster speed than that of the lower-frequency energy. This can enable "time gating" of the signals that arrive at the thermister array first to image features based on the highest frequency energy contained in a pulse. The highest frequency energy will also have the shortest wavelength. Significant high-frequency energy can be contained by a single, very short duration pulse. A pulse having a time duration ΔT will contain significant energy at a frequency, $f = 1/(\Delta T)$.

[0018]   For many thermally insulating materials, the thermal diffusivity, α, is on the order of 10^{-8} m^2/s. Thus, using the above equations, it can be shown that a laser sending a pulse having a duration, ΔT, of 10 ns would lead to a wavelength on the order of 10 nm. This is better than the diffraction limit of optical microscopes. It can be improved upon further with a femtosecond pulse laser, which would lead to a wavelength on the order of 1 nm. This is two orders of magnitude larger than the diffraction limit that can be achieved with electron microscopes. This method also avoids some of the negative features associated with electron microscopes, e.g., their high cost and the necessity of putting the specimen into a vacuum.

[0019]   FIG. 1 shows a specimen 10 positioned for analysis according to a first embodiment. Specimen 10 has possible discontinuities 12 therein and a thickness given at s. An array 14 of thermal sensors is positioned in thermal contact with a first side of specimen 10. A single thermal sensor of array 14 is identified at 16. Thermal sensors 16 can be thermistors or thermocouples and can also be realized as micro-electromechanincal system (MEMS) components. These sensors should be spaced from each other by at most one half wavelength of the temperature waves. Sensors 16 and array 14 can be electrically joined to a processor 18 to allow the processor 18 to image the specimen 10 from temperature variations at the

sensors 16. Heat is applied to specimen 10 by a pulsed laser
20. Pulsed laser 20 is capable of providing a single pulse of
light or multiple pulses as indicated by arrow 22 to a target
location 24 on specimen 10. Multiple pulses are provided at a
known pulse width ΔT and pulse frequency, f. The frequency or
color of the light in the pulse does not greatly affect heat
transfer to the specimen. Thus, it is more important to select
the laser based on the pulse frequency rather than the color of
light.

[0020]   In operation, pulsed laser 20 provides pulses of light
22 to target location 24 on specimen 10. Pulses of light 22
cause an increase in temperature at target location 24. The
temperature increase propagates to adjacent regions of specimen
10 by well-known heat transfer principles. Sensors 16 of array
14 measure the temperature of specimen 10 at the region of
contact with the sensor. The temperature waves propagating
through the specimen will interact with discontinuity 12 and
propagate to the sensor array contact surface of the specimen
10. Processor 18 collects the temperature measurements and
provides an output indicative of temperature propagation through
specimen 10. Processor 18 can time gate the array 14 output to
prevent spurious signals caused by reflection of the temperature
waves.

[0021] In a second embodiment, temperature is measured at a multiplicity of locations 26 on the first surface of specimen 10 by an infrared temperature detector 28. Infrared temperature detector 28 can be scanned across first surface to measure temperature at each location 26 to be measured. Infrared temperature detector 28 can be an infrared camera that images the entire first surface of specimen 10 at once. Infrared temperature detector 28 is joined to a processor 30 for analysis. Using an infrared detector doesn't have the same limitations as trying to measure infrared propagation through the material; however, the detector 28 must have sufficient resolution and precision to measure locations at intervals no greater than one half wavelength of the temperature waves.

[0022] This approach has the potential to resolve features on the order of nanometers, giving a much higher resolution than that of optical microscopes. The specimen, however, must have a thickness no more than about 10 wavelengths of the temperature waves. For example, temperature waves from a 1 ns pulse duration have a $1/\Delta T$ frequency, f = 1 GHz, and have propagation speed, c, through a typical specimen of about 10 m/s. Using the wave equation:

$$\lambda = \frac{c}{f} \tag{6}$$

gives a wavelength of 10 nm. Using equation (5) the wave

number, $k = 2\pi 10^8 \sqrt{-i} = 2.22 * 10^8(-1+i)$. Based on this, the original

temperature signal will decay to 1/e in approximately 10^{-8} m.

Depending on the sensitivity of the thermal array, the specimen

can have thickness s of up to 10λ or 100 nm.

[0023]   There is thus provided a method for non-destructivity

determining features embedded in a planar specimen, which method

is inexpensive, requires minimal sample preparation, can resolve

differences in thermal properties (e.g., thermal diffusivity),

which in some cases means resolving differences in material

composition, and can have a very low diffraction limit (based on

the laser pulse frequency), because of the slow propagation

speed.

[0024]   It will be understood that many additional changes in

the details, materials, steps and arrangement of parts, which

have been herein described and illustrated in order to explain

the nature of the invention, may be made by those skilled in the

art within the principle and scope of the invention as expressed

in the appended claims.

[0025]   The foregoing description of the preferred embodiments

of the invention has been presented for purposes of illustration

and description only. It is not intended to be exhaustive, nor

to limit the invention to the precise form disclosed; and

obviously, many modification and variations are possible in

light of the above teaching. Such modifications and variations

that may be apparent to a person skilled in the art are intended

to be included within the scope of this invention as defined by

the accompanying claims.

METHOD AND APPARATUS FOR NON-DESTRUCTIVELY
DETERMINING FEATURES IN A PLANAR SPECIMEN

ABSTRACT OF THE DISCLOSURE

A method and apparatus for non-destructively determining features in a planer specimen includes providing a heat impulse to the specimen, detecting temperatures in the specimen at a plurality of locations, and imaging the specimen from the detected temperatures. A laser can be used to provide a single or a plurality of heat impulses to the specimen. Temperatures in the specimen can be detected utilizing a contact sensor array or a remote infrared detector. These sensors are joined to a data processing device to image the specimen utilizing the detected temperatures.
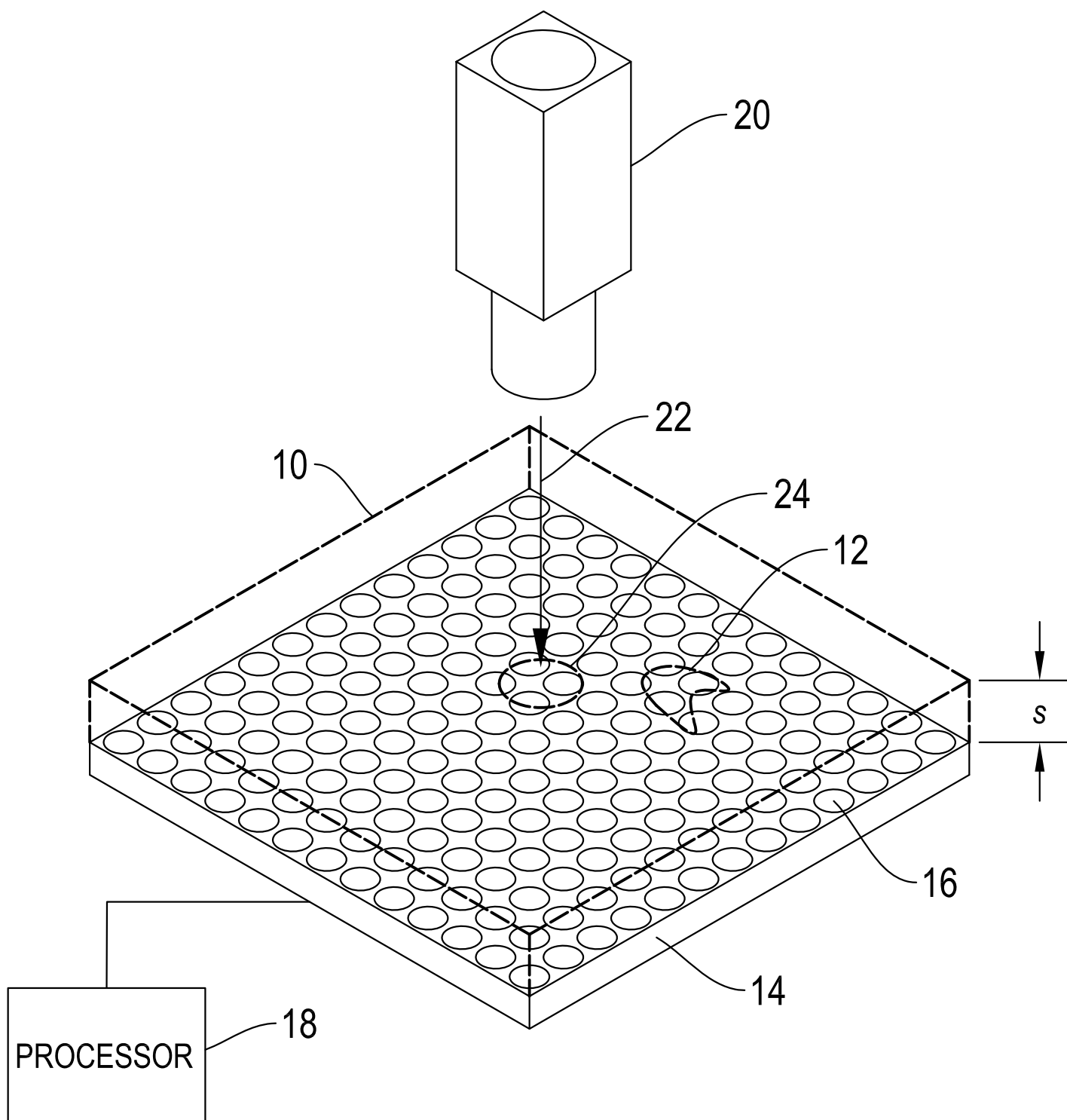
FIG. 1

PROCESSOR

FIG. 2